Earth Surface Processes and Landforms
Earth Surf. Process. Landforms, **23**, 809–824 (1998)

OVERBANK SAND DEPOSITION IN RELATION TO TRANSPORT VOLUMES DURING LARGE-MAGNITUDE FLOODS IN THE DUTCH SAND-BED RHINE RIVER SYSTEM

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Received 13 September 1996; Revised 29 December 1997; Accepted 15 January 1998

ABSTRACT

Using aerial photographs and field measurements, sandy overbank deposits formed by the large-magnitude floods of 1993/94 and 1995 were quantified along two branches of the Dutch Rhine river system: the Waal (1993/94 and 1995) and the IJssel (1995). These deposits were laid down intermittently all along the length of these rivers on the top and landward slope of the natural levees, and covered about 4 per cent of the embanked floodplain on the Waal and about 1 per cent on the IJssel. The overbanks and transport mechanism is basically convective by nature. The spatial variability of overbank sedimentation points to the important role played by helicoidal currents in determining overbank deposition.

The presence of embankments and training works appears to influence the sand transport to and morphological development of the floodplains along the Dutch Rhine river system. Overbank deposition volumes about equal present estimates of sand transport during a large-magnitude flood. It appears that studies on sand transport in the Dutch Rhine carried out so far underestimate sand transport during floods. © 1998 John Wiley & Sons, Ltd.

KEY WORDS: flooding; floodplain; overbank sedimentation; sand-bed river; sediment transport

INTRODUCTION

Overbank deposits are sediments laid down by a river on the floodplain surface during periods when high water is flowing or standing outside the channel (Wolman and Leopold, 1957). Although work on floodplain sediments has been concerned more with lateral accretion (point bar processes) than with overbank deposits (Marriott, 1992), overbank deposition is the dominant process in the development of the floodplain of a natural channel in unconsolidated material when this channel is laterally fixed for a long period of time (Stewart and LaMarche, 1967; Ritter *et al*., 1973). This is the case for some rivers in their natural state, such as the Delaware River over the last 6000 years (Ritter *et al*., 1973) and small coastal streams in Australia (Nanson and Young, 1981), and surely applies to the river Rhine in its present state where the planform is fixed by river training works.

Many studies on overbank deposition refer to sand and crevasse splays deposited by a single flood (McKee *et al*., 1967; Brown, 1983; Ritter, 1987; Marriott, 1992). Single flood thicknesses up to 60–90 cm have been reported (McKee *et al*., 1967) with the thickness and grain size of the overbank deposits usually decreasing with distance from the channel (Kesel *et al*., 1974; Hughes and Lewin, 1982; Gretener and Strömquist, 1987; Marriott, 1992). Studies usually focus on selected parts of more-or-less natural floodplains. This study deals with overbank deposition on the entire embanked floodplain of two branches of the Rhine river system in The Netherlands: the Waal and the IJssel. It attempts to quantify the importance of large-magnitude floods for the sediment budget of the Rhine river system, and it presents information on the exchange of sand between the main channel and the floodplain during flooding, information essential for understanding the dynamics of a

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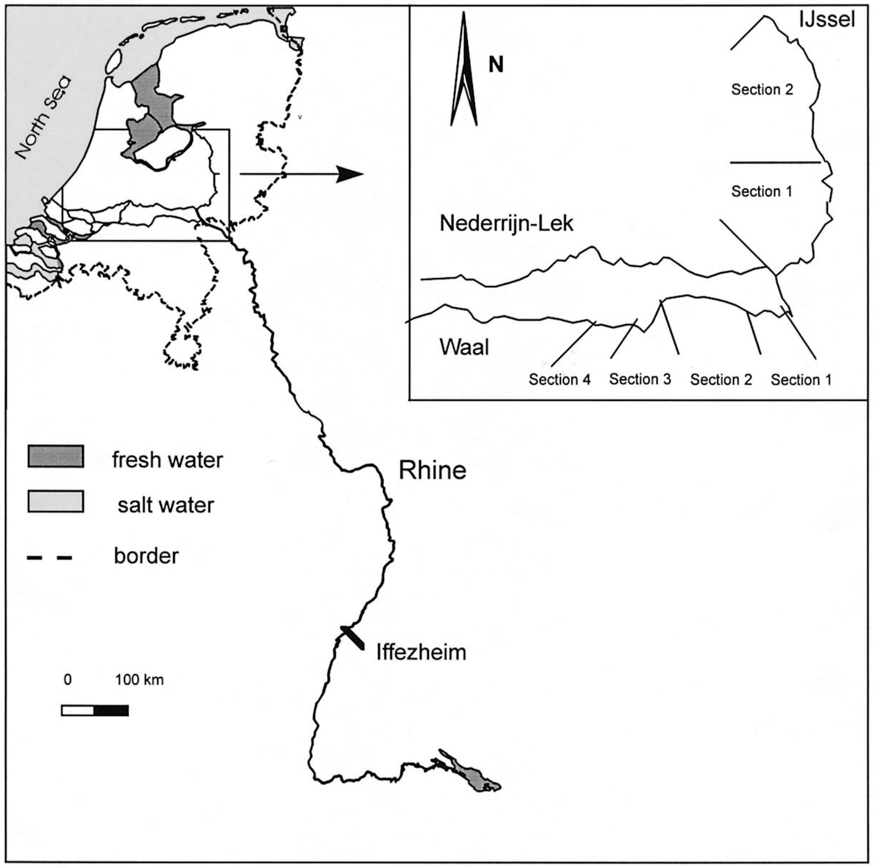

Figure 1. The Rhine river system, showing the branches Waal and IJssel in The Netherlands. The sections refer to the data in Tables IV, V and VI

river floodplain strongly influenced by man. The information may also help river authorities change a landscape presently dominated by pasture into a more natural one including sand accumulations (Langford, 1989) and natural levees.

THE AREA OF RESEARCH

The river Rhine is the most important river in western Europe. Its shipping density is highest of all the inland waterways of the world and its fresh water serves industrial, domestic and agricultural purposes, and prevents saline groundwater seepage into the Dutch polders. Man has affected and changed the river system over centuries. These changes include dredging and excavation works, artificial meander cut-offs, groynes, rip-rap on the river banks, weirs, and dams at the (former) river outlets. The present Dutch Rhine riparian landscape is mainly characterized by pastures, separated from the main channel by groynes. The policy of the Dutch authorities is to return riverine pastures to natural riparian zones without compromising the river's other functions. This is done: (i) actively, by creating secondary channels; and (ii) passively, by not affecting natural overbank deposition and thereby giving sand accumulations a chance to develop.

In The Netherlands the Rhine divides into three branches: the Waal, the Nederrijn-Lek and the IJssel (Figure 1). The discharge ratio between these branches is approximately 6:2:1. At the downstream end of the river Waal, water level is influenced by the tide only at low and moderate discharges. The river IJssel flows into Lake IJssel, formed by the closure of the former Zuiderzee in 1932, and thus has not been influenced by the tide since then. These branches have embankments constructed along the entire length within The Netherlands. The average

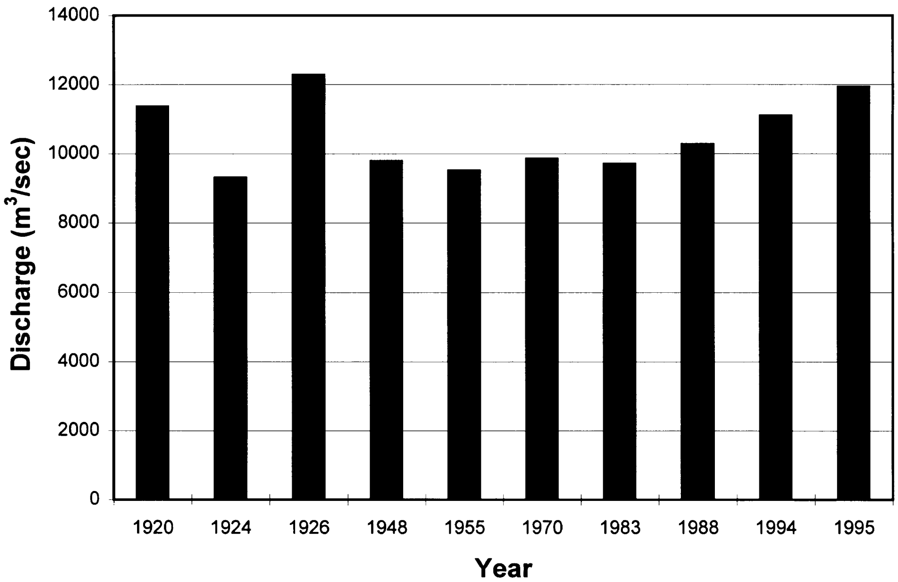

Figure 2. The 10 highest Rhine discharges since 1900

discharge of the Rhine near the Dutch–German border is 2300 $m^3 s^{-1}$, stemming from both rain and snowmelt. In Dec. 1993–Jan. 1994 and Jan.–Feb. 1995 the river Rhine experienced maximum discharges of 11 000 and 12 000 $m^3 s^{-1}$, respectively, among the highest Rhine discharges ever recorded (Figure 2).

Both the Waal and the IJssel are sand-bed rivers with median particle sizes of bed material of about 0·5–4 mm. The average depth of both rivers is in the order of 5 m and their lengths are 84 km and 123 km, respectively. The width of the Waal is 260–340 m whereas the width of the IJssel increases downstream from some 75 m at the bifurcation near Arnhem to 175 m at the outlet in Lake IJssel.

The middle and upper reaches of the Waal and IJssel have been subject to continuous bed degradation of 1–3 cm a^{-1} over the past five to six decades. This degradation, which is apparent in the entire freely flowing river Rhine downstream of the sluices near Iffezheim (Figure 1) (Gölz, 1994), may have led to a reduction of the frequency and period of overbank flow due to an increased wetted cross-section of the river at bankful discharge.

SEDIMENT TRANSPORT CHARACTERISTICS

In 1995 the upper 5–10 cm of the bed of the rivers Waal and IJssel was sampled at three positions across the river for cross-sections at regular distances of 1 km, and the grain-size composition was determined by nested sieving (Figure 3). The sediment of the bed is mainly sand for most of the river length. Upstream the bed is a mixture of sand and gravel.

Over the past decades the sediment transport in the Dutch Rhine branches has been studied by several researchers in different ways. This sediment transport is the bed material suspended load and bedload but is generally called sand transport because gravel is only a small part of the transported load. The results are summarized in Table I. The oldest data available are by Van Til (1956). He carried out several *in situ* measurements of suspended load and bedload sediment transport in all the Rhine branches for a large range of discharges, and used these data to test sediment transport formulae. He calculated the sediment transport for an average yearly discharge curve and for the large-magnitude flood of 1926 (Figure 2). In the 1980s and early 1990s again a series of *in situ* sediment transport measurements was carried out, also for different discharges and addressing both suspended load and bedload. From these measurements relationships between discharge and sediment transport were determined, and from these relationships and the yearly discharge curves the yearly sediment transport was calculated for the period 1980–95 (Kleinhans, 1996). Van Dreumel (1995)

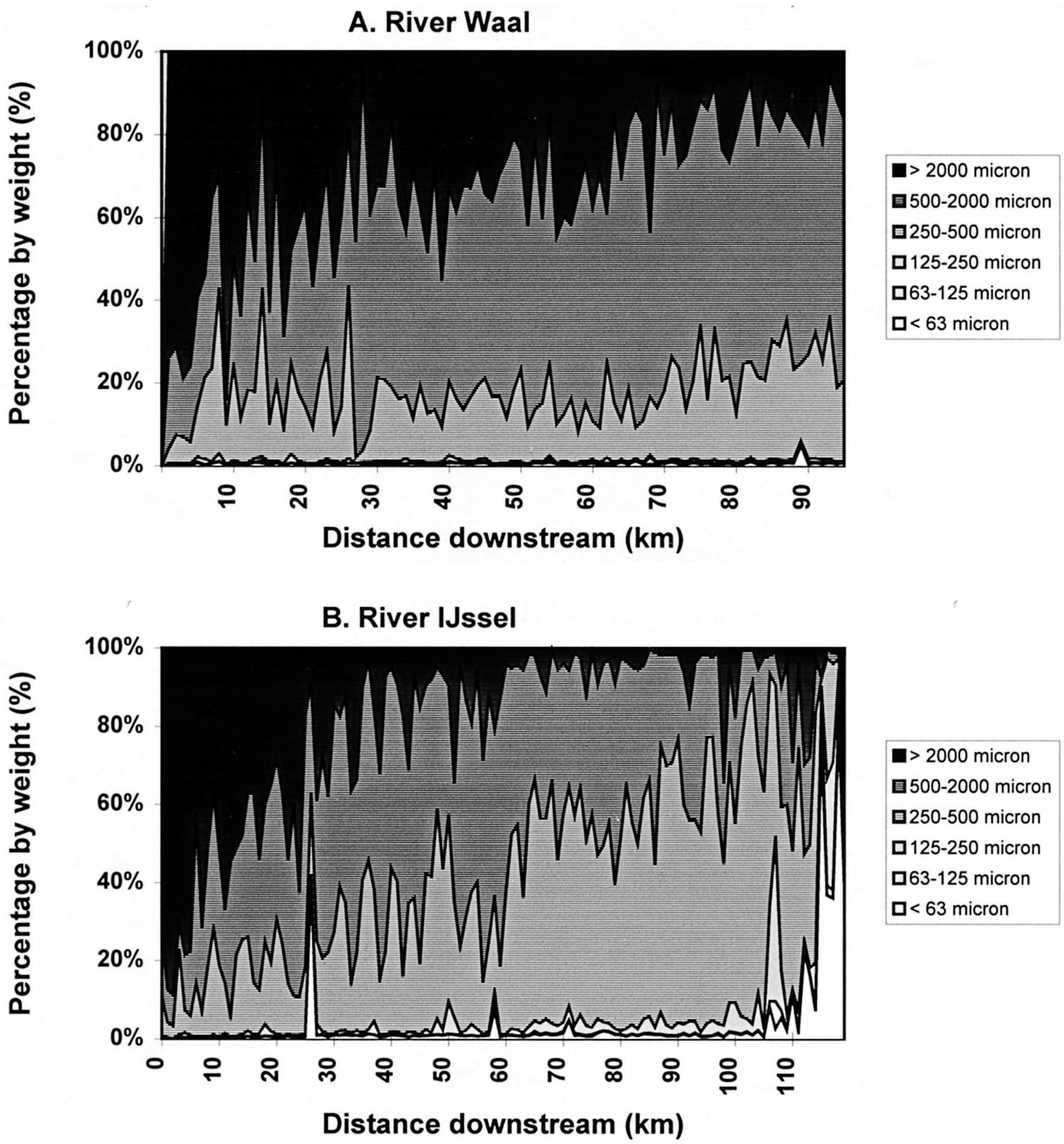

Figure 3. The grain-size composition of the bed of the rivers Waal (A) and IJssel (B) versus distance along the river

produced a sediment budget for the downstream, estuarine part of the Rhine–Meuse river system, based on a detailed study of soundings, dredging works and sediment transport measurements in this area over the period 1982–92. From this budget the yearly sand output from the river Waal was calculated. Dröge (1992) quantified the sediment transport output volume of the German Niederrhein from transport measurements and echo-soundings in this area. Most of this output is input into the Waal.

Table I shows that average yearly transport of bed material in the Waal is roughly 500 000 m^3 a^{-1} and is about 10 times as large as that in the IJssel. The sediment transport during a large-magnitude flood can also be estimated from the data in Table I by subtracting the data for an average year from the data for a year with a flood for the data of Van Til and Kleinhans, respectively. Thus for the Waal sediment volumes of 225 000, 199 000 and 177 000 m^3 per flood are calculated for the floods of 1926, 1988 and 1995, respectively.

Table I. Bed material sediment transport in the Waal and IJssel according to several studies over the past decades (values × 1000 m^3 a^{-1}). The data of Van Til and Kleinhans refer to the upstream and those of Van Dreumel to the downstream part of the Waal. The data of Dröge refer to a position 10 km upstream of the Waal

	Conditions	Reference	Bedload	Suspended	Total
Waal					
1901–50	Average year	Van Til (1956)	175	110	285
1926	Year with flood	Van Til (1956)	265	245	510
1980–95	Average year	Kleinhans (1996)	287	368	655
1988	Year with flood	Kleinhans (1996)	319	535	854
1995	Year with flood	Kleinhans (1996)	314	518	832
1982–92	Average year	Van Dreumel (1995)			700*
	Average year	Dröge (1992)			412†
IJssel					
1901–50	Average year	Van Til (1956)	35	5	40
1926	Year with flood	Van Til (1956)	45	10	55
1980–95	Average year	Kleinhans (1996)	23		
1988	Year with flood	Kleinhans (1996)	29		
1995	Year with flood	Kleinhans (1996)	28		

* A dry density of 1500 kg m^{-3} was assumed
† Data refer to particles >200 µm

METHODS AND ANALYSES

Immediately after the high discharges of 1993/94 and 1995 had subsided and the floodplain emerged, oblique aerial photographs were taken of the entire floodplain in between the embankments along the Dutch Rhine branches. This was done on 10 March 1994 and 22 March 1995, respectively. The sand splays were mapped using photos of the Waal of both years and photos of the IJssel for 1995. These maps were then taken into the field and the observed deposits were checked by measuring the width of the sand splays at several transects perpendicular to the channel. The transects were distributed evenly across the splays, 75 m apart, a distance that was chosen based on a pilot study that showed that splay volumes could be measured with satisfactory accuracy and modest effort at that distance.

Along each transect the thickness of the deposits to within 1 cm was measured at 5 m intervals by pushing a PVC tube into the sand down to the buried turf. The technique was checked by excavating to the buried turf at a sample of locations. The sand in between the groynes was not considered because here no buried grass stems and roots could be used to identify the pre-flood surface. At some locations along the Waal the overbank deposits of 1995 were on top of the deposits of 1993/94 without vegetation in between. Where these deposits were separated by a clay-rich layer, this layer was used as a marker representing a period with stagnant water in between the floods. Deposits where no dividing marker could be identified were not considered further. The total amount of overbank deposits, therefore, is a conservative estimate.

The parts of the floodplain where no recent sand splays could be observed on the aerial photographs may have experienced some deposition. This amount, called ‘background sedimentation’, was quantified by measuring the sand thickness in 25 transects perpendicular to the channel in between the sand splays. These transects were located on both river banks. On both banks approximately 5 km were built on and therefore showed no deposits.

From the areas of the sandy deposits derived from the aerial photographs and field observations, and the thicknesses measured in the field, volumes were calculated. The areas were analysed by GIS (ARC-INFO) and the overlap between the areas, showing deposits in 1994 and 1995, was calculated.

RESULTS

Overbank deposition volumes

Due to their light coloration the overbank deposits on the embanked floodplain could be observed very clearly on the aerial photographs (Figure 4). These deposits were observed at patchy sand splays on top and on

Figure 4. Oblique aerial photograph of overbank deposits along the IJssel in 1995

the landward slope of the natural levees along the rivers Waal and IJssel (Figures 5 and 6). Locally, oblong splays were observed, characterized by relatively thick deposits and distinct lateral margins (Figure 7).

The total length, average thickness and width, and total area and volume of the overbank deposits along the rivers Waal and IJssel are presented in Tables II and III, respectively. The data on the distinct deposits, observed on the photographs and checked in the field, and the background deposits on the other parts of the floodplain are presented separately and summed to obtain the total volumes. These total volumes were 169 000 and 217 000 m^3 for the Waal in 1993/94 and 1995, respectively, and 46 000 m^3 for the IJssel in 1995. The volumes on the left bank of the Waal were larger than the volumes on the right bank both in 1993/94 and in 1995 (Table II). For the IJssel the difference between both banks was negligible (Table III). A few sand splays observed in 1993/94 and 1995 were not included in the calculations for the Waal (Table II) because no dividing marker for the 1993/94 and 1995 deposits could be identified. The volumes in Table II are therefore conservative estimates. An indication of this underestimation may be quantified by assuming that the volumes of these splays in 1994 and

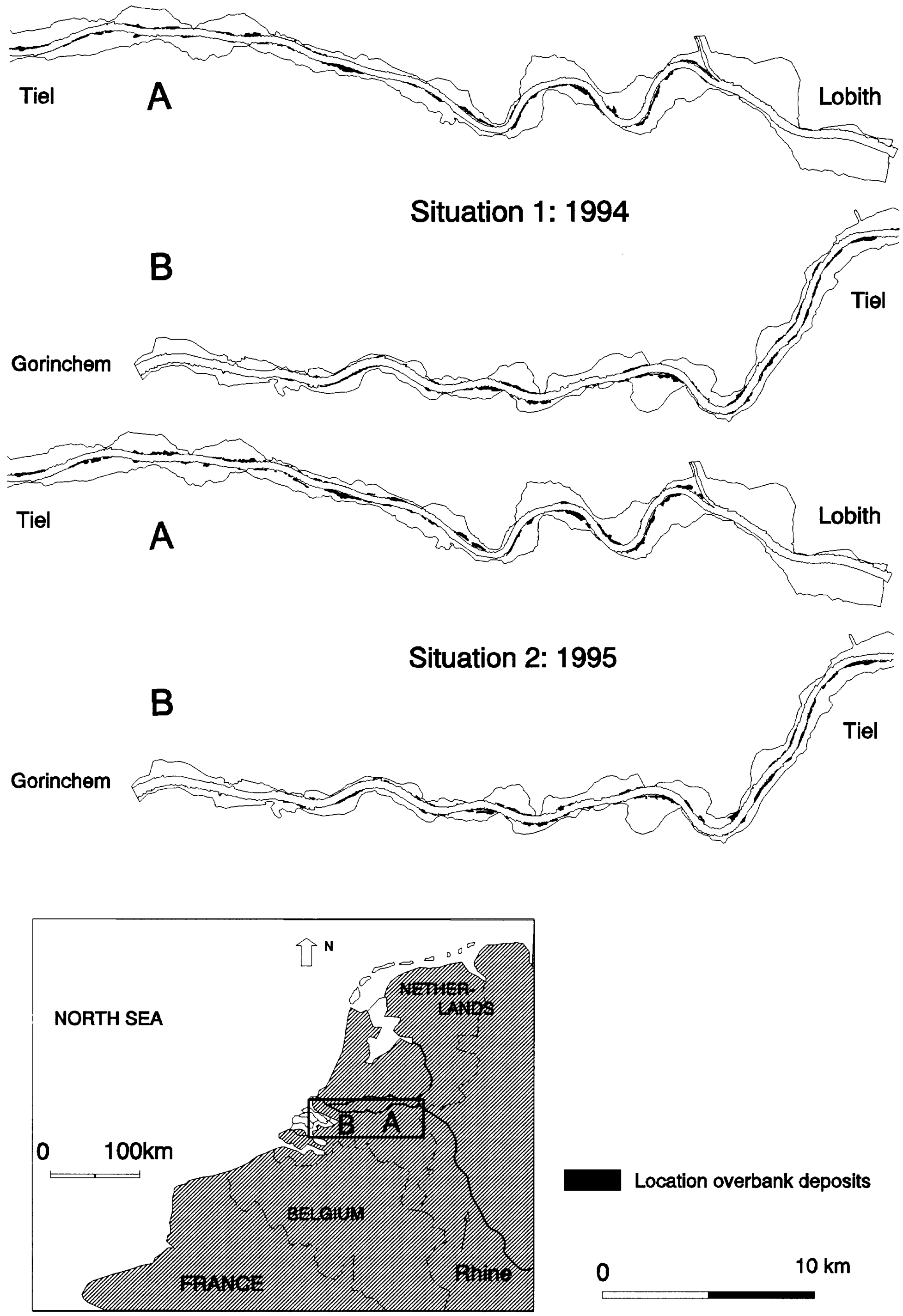

Figure 5. Sand and crevasse splays along the river Waal deposited by overbank flow in 1993/94 and 1995

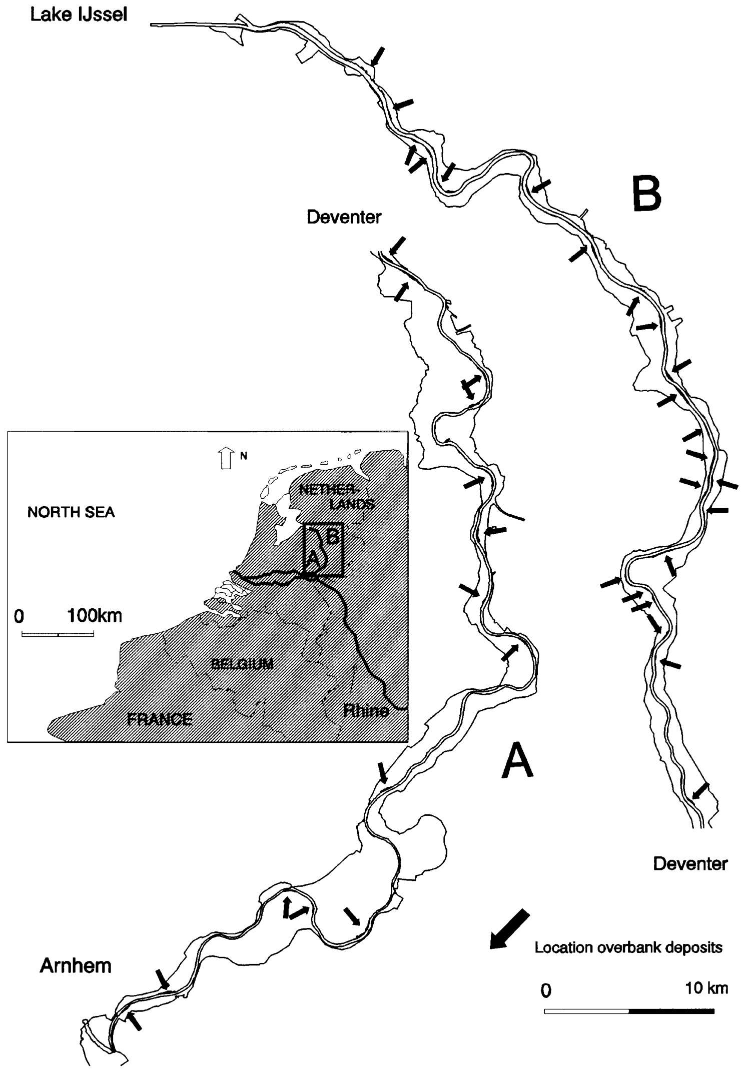

Figure 6. Sand and crevasse splays along the river IJssel deposited by overbank flow in 1995

the extra volumes in 1995 were deposited by the floods of 1993/94 and 1995, respectively. Thus, overbank deposition in Table II may be underestimated by at most 16 per cent for the 1993/94 flood and 22 per cent for the 1995 flood.

Spatial variability

The spatial pattern of overbank deposits along the Waal was studied in more detail by subdividing the Waal into four sections (Figure 1) and comparing the volumes of overbank deposits on the inner and outer banks, and straight reaches within these sections. This subdivision is based on differences in the long-term behaviour of the river bed and differences in planform. Section 1 is the upstream sinuous section of the Waal, which has been subject to erosion over the past few decades. In sections 2, 3 and 4 periods of both river bed erosion and deposition have taken place during these decades. Sections 2 and 4 are more-or-less straight reaches. Section 3 is sinuous.

In Table IV the volumes of overbank deposition are shown. The overbank deposits are made up almost entirely of the spatially discrete deposits observed on the photographs; the volumes of background sedimentation were relatively modest. The discrete deposits covered only a few per cent of the entire floodplain.

Figure 7. Crevasse splay on the floodplain of the Waal in 1995

From the total volumes of overbank deposition and the length of the banks in the discriminated sections of the river, the overbank sediment transport per running metre bank was calculated. Transport fluxes were highest in the sinuous sections 1 and 3 in both years. Overall, during both floods about 1 m^3 per running metre bank was transported from the main channel onto the floodplain. The overlap of the areas receiving discrete deposits in both years was between 55 and 70 per cent.

Similarly, the IJssel was subdivided into two sections (Figure 1) based on a change of river bed gradient halfway with the bed gradient of section 1 being steepest (Table V). Again, overbank deposition was mainly made up of spatially discrete deposits which covered about 1 per cent of the floodplain. Coverage and transport per running metre bank were about twice as high in section 2 (1·12 per cent; 0·24 m^3 m^{-1} per flood) compared to section 1 (0·48 per cent; 0·13 m^3 m^{-1} per flood).

Coverage and overbank fluxes along the Waal (Table IV) were roughly five times those along the IJssel (Table V). In all sections of the Waal and IJssel floodplains, and in both years, the volumes of overbank deposits on the inner banks far exceeded the volumes on the outer banks (Figure 8).

Table II. Sandy deposits on the (natural) levees and floodplain of the Waal due to the floods of Dec. 1993–Jan. 1994 and Jan.–Feb. 1995. The area and volume percentages refer to the comparative contribution of left and right bank to the total amounts

	1993/94			1995		
	Left bank	Right bank	Total	Left bank	Right bank	Total
River length (km)	84·2	84·2	168·4	84·2	84·2	168·4
Discrete deposits						
Total length (km)	47·7	27·7	75·4	37·7	24·0	61·6
Average thickness (cm)	4·9	5·4	5·1	6·8	5·2	6·2
Average width (m)	47·0	37·7	43·6	58·0	47·5	53·9
Total area (km^2)	1·8	1·0	2·8	1·9	1·2	3·1
Total area (%)	63	37	100	63	37	100
Total volume (m^3)	88 214	56 665	144 879	133 011	59 637	192 648
Total volume (%)	61	39	100	69	31	100
Background sedimentation						
Average thickness (cm)	0·7	1·0	0·8	1·1	0·8	1·0
Total volume (m^3)	9114	14 703	23 817	15 920	8805	24 725
Total volume (%)	38	62	100	64	36	100
Discrete deposits + background						
Total volume (m^3)	97 328	71 368	168 696	148 931	68 442	217 373
Total volume (%)	58	42	100	69	31	100

Table III. Sandy deposits on the (natural) levees and floodplain of the IJssel due to the flood of Jan.–Feb. 1995. The area and volume percentages refer to the comparative contribution of left and right bank to the total amounts

	1995		
	Left bank	Right bank	Total
River length (km)	123·0	123·0	246·0
Discrete deposits			
Total length (km)	20·4	9·6	30·0
Average thickness (cm)	4·1	6·0	4·8
Average width (m)	25·6	29·7	26·9
Total area (km^2)	0·5	0·3	0·8
Total area (%)	65	35	100
Total volume (m^3)	21 591	16 918	38 509
Total volume (%)	56	44	100
Background sedimentation			
Average thickness (cm)	0·3	0·4	0·4
Total volume (m^3)	2928	4338	7266
Total volume (%)	40	60	100
Discrete deposits + background			
Total volume (m^3)	24 519	21 256	45 775
Total volume (%)	54	46	100

DISCUSSION

The impact of embankments and training works

Overbank deposition of sand by large-magnitude floods in the investigated Dutch Rhine branches occurred only in a limited area. Discrete sandy deposits, observed as white splays on aerial photographs and making up most of the overbank sand transport, covered the floodplains of the rivers Waal and IJssel by approximately 4 per cent and 1 per cent, respectively. Sand deposition was restricted mainly to the top and landward slope of the natural levees; most of the floodplain was not affected by overbank deposition of sand. It would be interesting to compare the extent of overbank deposition on the embanked Dutch floodplains with data on more-or-less natural floodplains in the literature. This comparison is complicated, however, by the fact that data in the

Table IV. Distribution of sandy overbank deposits over four sections along the river Waal

	Section 1	Section 2	Section 3	Section 4	Entire Waal
1993–94					
River length (km)	22	33	10	19	84
Thickness of deposits (cm)	5·8	4·5	5·1	5·0	5·1
Area of deposits (km^2)	0·8	1·0	0·5	0·5	2·8
Volume of deposits (m^3)	49 016	44 518	26 571	24 774	144 879
Cover floodplain (%)	3·33	2·83	4·17	3·66	3·30
Background sedimentation (m^3)	6991	9684	3437	3705	23 817
Total overbank deposition (m^3)	56 007	54 202	30 008	28 479	168 696
Transport ($m^3 m^{-1}$ $flood^{-1}$)	1·27	0·82	1·50	0·75	1·00
1995					
River length (km)	22	33	10	19	84
Thickness of deposits (cm)	7·9	5·7	6·0	4·7	6·2
Area of deposits (km^2)	1·0	1·1	0·5	0·6	3·1
Volume of deposits (m^3)	74 940	61 551	29 887	26 270	192 648
Cover floodplain (%)	3·76	3·09	4·03	4·18	3·59
Background sedimentation (m^3)	7258	10 053	3568	3846	24 725
Total overbank deposition (m^3)	82 198	71 604	33 455	30 116	217 373
Transport ($m^3 m^{-1}$ $flood^{-1}$)	1·87	1·08	1·67	0·79	1·29
Overlap both floods with respect to 1993/94 (%)	69·5	69·5	55·0	64·7	66·0

Table V. Distribution of sandy overbank deposits over two sections along the river IJssel (data for 1995)

	Section 1	Section 2	Entire IJssel
Length (km)	61	62	123
Bed gradient ($\times 10^{-5}$)	11·0	4·0	7·4
Thickness of deposits (cm)	4·4	5·0	4·8
Area of deposits (km^2)	0·3	0·5	0·8
Volume of deposits (m^3)	12 380	26 129	38 509
Cover floodplain (%)	0·48	1·12	0·76
Background sedimentation (m^3)	3887	3379	7266
Total overbank deposition (m^3)	16 267	29 508	45 775
Transport (m^3 m^{-1} $flood^{-1}$)	0·13	0·24	0·19

literature refer to selected parts of floodplains only. With respect to the proportion of the floodplain covered by sandy overbank deposits due to flooding, values ranging from 10 per cent for a relatively modest flood in a sand-bed river (flood recurrence interval = 11–12 years, bed gradient = $4 \cdot 4 \times 10^{-4}$) (Erskine and Melville, 1983) to over 70 per cent for a large-magnitude flood in a sand–gravel–bed river (flood recurrence interval = 100 years, bed gradient = 0·02) (Stewart and LaMarche, 1967) have been reported. These data are probably not representative for the process on the scale of the entire river trajectory. They do show, however, that in these rivers overbank sand transport may locally affect a significant part of the floodplain. For the Dutch rivers this is not the case.

The modest coverage of the floodplain of the Dutch Rhine branches by recent overbank deposits most probably is largely due to the fact that these branches have been embanked and their planform has been fixed for centuries. Due to sedimentation over the course of time the floodplain surface is now relatively high when compared to the surrounding land outside the dykes. Besides, most of the river bed of the Waal and IJssel has been subject to a continuous lowering because of net erosion. This bed degradation has taken place continuously over the past decades at a rate of 1–3 cm a^{-1} (unpublished results). Therefore, one might expect floodplain sedimentation rates to decrease with time because of (i) a reduced flooding frequency and inundation time, and (ii) a reduced sediment transport capacity of the water flowing outside the channel. Middelkoop (1997) quantified average floodplain sedimentation rates over different periods of time, by studying the beginning of sedimentation from historic maps (250 years), heavy metal profiles in floodplain soils (100 years), and contemporary sedimentation at the event scale (1 year), and concluded that floodplain sedimentation rate for the Waal during the past two centuries had indeed reduced by 70 per cent. Besides, sedimentation on most of

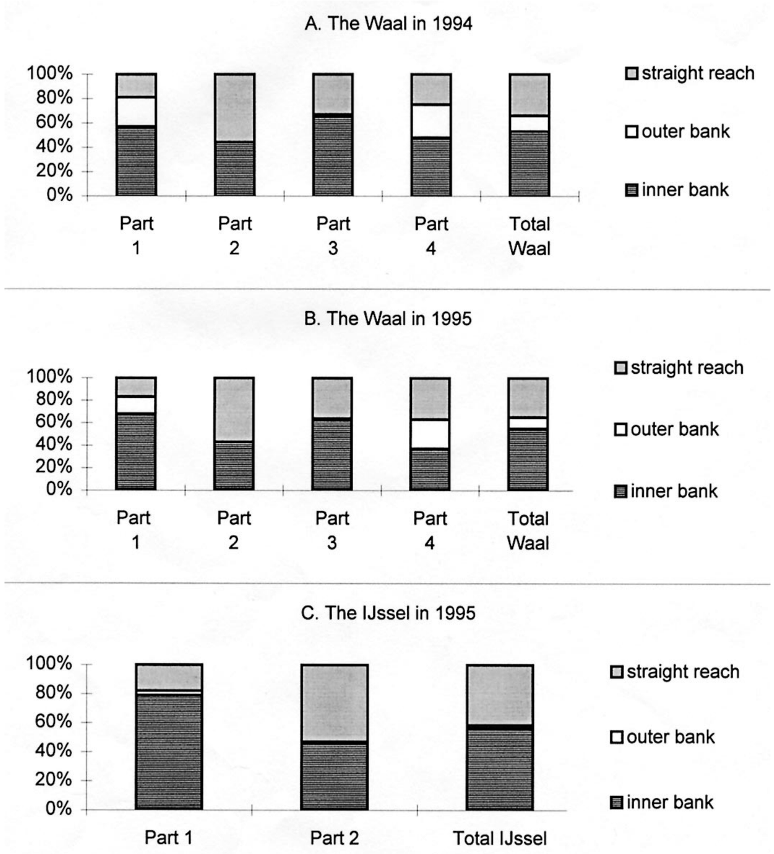

Figure 8. Distribution of sandy overbank deposits along the Waal and IJssel over the inner and outer banks, and the straight reaches

the floodplain is now due to the finest, cohesive sediments only, indicating that current velocities on most of the floodplain are insufficient to transport coarse sediments (Asselman and Middelkoop, 1995).

Training works such as groynes and rip-rap, which are all along the banks of these rivers, probably also limit overbank sand transport onto the Dutch floodplains. These training works dissipate the energy of the currents and protect the sediments in between from erosion and transport to the levees.

Spatial variability

In sinuous rivers helicoidal currents induce erosion of sediments in the concave (outer) bank, which are subsequently transported to and deposited in the convex (inner) bank. Results presented here show that during large-magnitude floods helicoidal currents are important for overbank sand transport. Because of this process the volumes of sandy overbank deposits on the inner bank far exceed those on the outer bank (Figure 8). Similar observations have been made elsewhere (Kesel *et al*., 1974). According to Hooke (1975) this strong difference in the amount of overbank deposition on the levees of the inner and outer banks illustrates the phenomenon that the strength of the helicoidal current increases as discharge rises. This results in an increase of sediment transport from the outer to the inner bank. The flux of overbank sand, therefore, should be much larger in a sinuous section of the river when compared to straight reaches. In Figure 9 the flux of overbank sand is plotted versus sinuosity (ratio of channel length to valley length) for the four sections of the Waal and both years. Overbank sand transport clearly increases with sinuosity, suggesting an important role for helicoidal currents.

Generally, overbank deposits are most abundant in the middle and lower reaches of rivers due to factors such as decreasing bed gradient, rising baselevel, and high frequency and magnitude of overbank flows (Nanson and

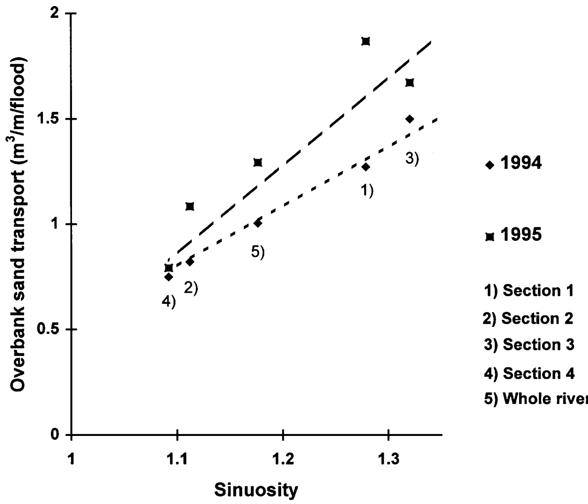

Figure 9. Overbank sand transport flux versus river sinuosity for the four sections of the Waal and both years

Young, 1981; Zwolinski, 1992). The larger volume of overbank deposits in section 2 of the IJssel when compared to section 1 (table V) agrees with this general tendency. For the Waal this effect is overridden by the higher sinuosity of the upstream section.

The volumes of overbank deposits on the left bank exceeded those on the right bank for the river Waal in both years. This may have been due to shipping. On the river Waal loaded vessels sailing from Rotterdam harbour to Germany generally follow the left bank whereas the empty vessels returning to Rotterdam follow the right bank. Both vessels sailing up- and downstream induce currents in between the groynes which at times are strong enough to erode the relatively fine-grained sediments and transfer these to the river bed near the bank. The strength of these currents depends on the water volume that is displaced during vessel movements. This displacement flow is strongest for the loaded vessels because of the larger submerged cross-sectional area of the vessels (Bhowmik *et al*., 1995). Erosion of the sand in the areas in between the groynes due to navigation traffic, therefore, is thought to be most apparent near the left bank. Because of the high shipping density, this is probably a more-or-less continuous process which may result in a different grain size composition for the left part of the river bed relative to the right part. This has been investigated for 1966, 1976, 1984 and 1995. In these years the left and right parts of the river bed of the entire Waal were sampled at intervals of 1 km. From these grain-size distributions the percentiles D10, D50 and D90 have been calculated. The results, averaged for the entire Waal, are presented in Figure 10. River bed sediment near the left bank is finer grained than near the right bank. The difference is statistically significant according to Wilcoxon signed-ranks test ($p<0{\cdot}05$). These results indicate that vessel-induced erosion of sandy sediments in between the groynes may be a significant source of sand for transport to the (left part of the) river bed. A part of this resuspended sediment may also be transported onto the floodplain during overbank flow.

Overbank transport processes: convection versus diffusion

Overbank sand transport is due to turbulent diffusion and/or convection. Turbulent diffusion results from the difference in current velocities between the channel (fast and deep flow) and the floodplain (slow and shallow flow). The transfer of momentum and suspended sediment results in floodplain deposits which decrease in thickness, decrease in grain size and increase in sorting with increasing distance from the channel (Nanson, 1980). Diffusion underlies the model of overbank deposition by Pizzuto (1987). Overbank deposition by diffusion is restricted to a narrow strip close to the channel.

Sediment transfer by convection may occur where there is a component of flow perpendicular to the channel. Convection may result in strong differences in the amounts of sediment deposited on both levees of the river. Besides diffusion, convection is also used in the model of James (1985). Convective transport often results in crevasse splays (Ritter, 1987; Marriott, 1992).

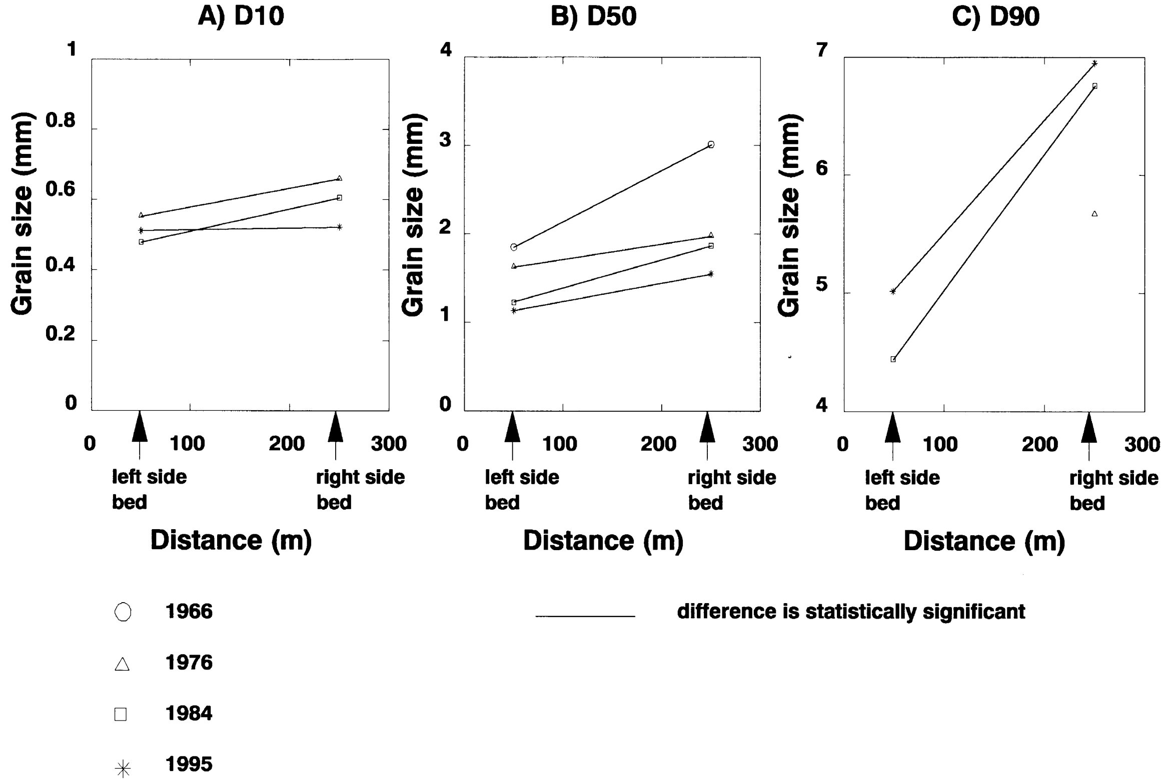

Figure 10. Grain-size characteristics of river bed sediment of the Waal near the left and right bank in 1966, 1976, 1984 and 1995

The pattern of overbank deposits reflects the overbank transport processes. Clearly, convective sand transport by helicoidal currents is important. Convective sand transport across the levees and further onto the floodplain, however, is insignificant. Probably the embankments and training works all along the rivers Waal and IJssel confine the high velocity currents to the main channel and prohibit strong currents traversing the floodplain inclined to the main channel. Numerical model output of the discharge distribution across the rivers Waal and IJssel during a simulated flood shows that the locations of sand splays close to the channel agree favourably with the locations where the water is flowing onto the floodplain. Apparently, the flow on the floodplain became overloaded with sediment from turbulent and turbid water from the channel and this resulted in deposition close to the channel. These deposits closely resembled the pattern of overbank deposits along the Severn discussed by Marriott (1992). Comparing textural analyses of overbank deposits with sand distributions predicted by the model of James (1985), Marriott concluded that overbank sand transport for the Severn may be modelled by analogy with a diffusion process. The agreement of the pattern of overbank deposits with the calculated discharge distribution for the Waal and IJssel, however, indicates that the overbank transport mechanism is basically convective by nature.

Sediment transport in the channel: the importance of floods

One of the aims of this study was to quantify the importance of large-magnitude floods for the sand budget of the Rhine river system. This sand budget consists of (1) an upstream sand input, (2) a downstream sand output, (3) a sand source due to net erosion of the bed, and (4) a sand sink due to overbank deposition. The sand input during an entire flood is estimated at 200 000 m^3, based on the results in Table I and the discussion above (in the section of 'sediment transport characteristics'). The sand source (3) is estimated from the average river bed degradation rate over the past 10 years. The sand output results from the other terms. The budget was produced for the four sections of the river Waal (Table VI). The volumes of sandy overbank deposition in 1993/94 and 1995, 169 000 m^3 and 217 000 m^3, respectively, are of the same order of magnitude as the estimated sand input

Table VI. River bed degradation and overbank deposition in four sections of the Waal during the floods of 1993/94 and 1995, and the resulting lateral reduction of sand transport (×1000 m^3 per flood)

	Length (km)	Input	Degradation	Overbank deposition	Output
Flood 1993/94					
Section 1	22	*200*	23	–56	167
Section 2	33	167	21	–54	134
Section 3	10	134	2	–30	106
Section 4	19	106	–10	–28	*67*
Entire Waal	84	*200*	36	–169	*67*
Flood 1995					
Section 1	22	*200*	23	–82	141
Section 2	33	141	21	–72	91
Section 3	10	91	2	–33	59
Section 4	19	59	–10	–30	*19*
Entire Waal	84	*200*	36	–217	*19*

Negative values indicate transport out of channel section

upstream. Since the estimated amount of sand eroded from the river bed due to degradation is relatively small (36 000 m^3 a^{-1}), a steadily reducing sand transport component downstream results from sedimentation on the river banks. From these data a Waal sand output of 19 000–67 000 m^3 during a major flood is calculated. In this calculated budget the sink term is a conservative estimate since (i) the amounts of sandy overbank deposits are underestimated, probably up to 16 and 22 per cent for 1993/94 and 1995, respectively, and (ii) sediment deposition in between the groynes was not considered. The amount of sediment transport from the channel into the areas in between the groynes is unknown. It is hypothesized that these areas accumulate a lot of sand during floods which is transferred to the river again due to vessel-induced currents throughout the year.

From the foregoing it is clear that the upstream sand load during a major flood must be larger than 200 000 m^3 per flood. An input of 200 000 m^3 per flood results in a depletion of sand load downstream which is unrealistic according to the long-term Waal sand output of 58 000 m^3 per month by Van Dreumel (Table I). This is an average value over a 10 year period and therefore includes a wide range of discharges. Considering that (i) the sand output of 58 000 m^3 per month refers to a combination mostly of modest discharges with occasionally (about once every two years) an overbank flow event, one might conclude that downstream river output during a major flood must be more than 19 000–67 000 m^3

CONCLUSIONS

Overbank deposition along the Waal by the large-magnitude floods of 1993/94 and 1995 was estimated to be 169 000 m^3 and 217 000 m^3, respectively. Along the IJssel only about 46 000 m^3 was deposited. They occurred as distinct deposits on the top and landward slope of the levees along both rivers and covered the floodplains within the embankments up to 4 per cent and 1 per cent of their area, respectively.

From the pattern of sandy overbank deposits it appears that overbank sand transport in the Dutch Rhine river system is basically convective by nature. In particular helicoidal currents play an important role. Because of these currents, volumes of sandy overbank deposition on the inner bank far exceeded those on the outer bank.

Along the Dutch Rhine river system, sand transport onto the floodplains and the morphological development of these floodplains are influenced by the presence of river training works and embankments. Therefore, the amount of sandy overbank deposition along these Rhine branches is not necessarily related to the amount of sand transported through the channel during a flood. From a discussion of data on sand transport, erosion and deposition in the river Waal it may be concluded that the sand load into the Waal during the floods of 1993/94 and 1995 must have been more than 200 000 m^3. A detailed understanding of river morphodynamics depends on a detailed knowledge of sediment transport during floods.

ACKNOWLEDGEMENTS

The authors wish to thank Rijkswaterstaat, Directorate Eastern Netherlands for financing the aerial photographs and coordinating the photo campaign. B. Kornman, G. R. van Manen, Y. Onneweer, A. Lam, P. van de Ring, M. van Dinter, G. de Vaan and A. Borsboom (Utrecht University) are thanked for carrying out the fieldwork, W. H. M. Janssen and L. Schutte (Rijkswaterstaat, RIZA) for their assistance with the GIS activities, and several colleagues for their valuable comments on an earlier draft of this paper. The manuscript benefited from critical reviews by Dr T. Spencer, Dr G. C. Nanson and an anonymous referee.

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